Near-infrared Observations of Be/X-ray Binary Pulsar A0535+262

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Abstract We present results obtained from an extensive near-infrared spectroscopic and photometric observations of the Be/X-ray binary A0535+262/HDE 245770 at different phases of its ∼111 day orbital period. This observation campaign is a part of the monitoring programme of selective Be/X-ray binary systems aimed at understanding the X-ray and near-IR properties at different orbital phases, especially during the perisastron passage of the neutron star. The near-IR observations presented here were carried out using the 1.2 m telescope at Mt. Abu IR observatory. Though the source was relatively faint for spectroscopic observations with the 1.2 m telescope, we monitored the source closely during the 2011 February–March giant X-ray outburst to primarily investigate whether any drastic changes in the near-IR JHK spectra take place at the periastron passage. Changes of such a striking nature were expected to be detectable in our spectra. Photometric observations of the Be star show a gradual and systematic fading in the JHK light curves since the onset of the X-ray outburst that could suggest a mild evacuation/truncation of the circumstellar disc of the Be companion. Near-IR spectroscopy of the object shows that the JHK spectra are dominated by the emission lines of hydrogen Brackett and Paschen series and HeI lines at 1.0830 μm, 1.7002 μm and 2.0585 μm. The presence of all hydrogen emission lines in the JHK spectra, along with the absence of any significant change in the continuum of the Be companion during X-ray quiescent and X-ray outburst phases suggest that the near-IR line emitting regions of the disc are not significantly affected during the X-ray outburst.

Key words: infrared: stars – Be, binaries – stars: individual (A0535+262)– techniques: spectroscopic

1 INTRODUCTION

High mass X-ray binary (HMXB) systems are strong X-ray emitters via the accretion of matter from the OB companion onto the neutron star. These objects appear as the brightest objects in the X-ray sky. The HMXBs are classified as Be/X-ray binaries and supergiant X-ray binaries. The Be/X-ray binaries represent the largest subclass of HMXBs. In Be/X-ray binaries, the optical companion is a Be star. These Be stars are fast rotating B-type stars which show spectral lines such as hydrogen lines (Balmer and Paschen series) in emission (Porter & Rivinius 2003 and references therein). Apart from hydrogen lines, the stars occasionally show He, Fe lines in emission (Hanuschik 1996). These objects also show infrared excess i.e an amount of IR radiation that is larger than that expected from an absorption-line B star of the same spectral type. The origin of the emission lines and infrared excess in Be/X-ray binary systems are attributed to the presence of a circumstellar gaseous component around the Be star that is commonly accepted to be in the form of equatorial disc. The disc is believed to be fed from the material expelled from the rapidly rotating Be star (Porter & Rivinius 2003). The orbit of Be/X-ray binary systems is generally wide (with orbital period in the range of tens of days to several hundred days) and eccentric (with eccentricity e in the range of 0.1 to 0.9)

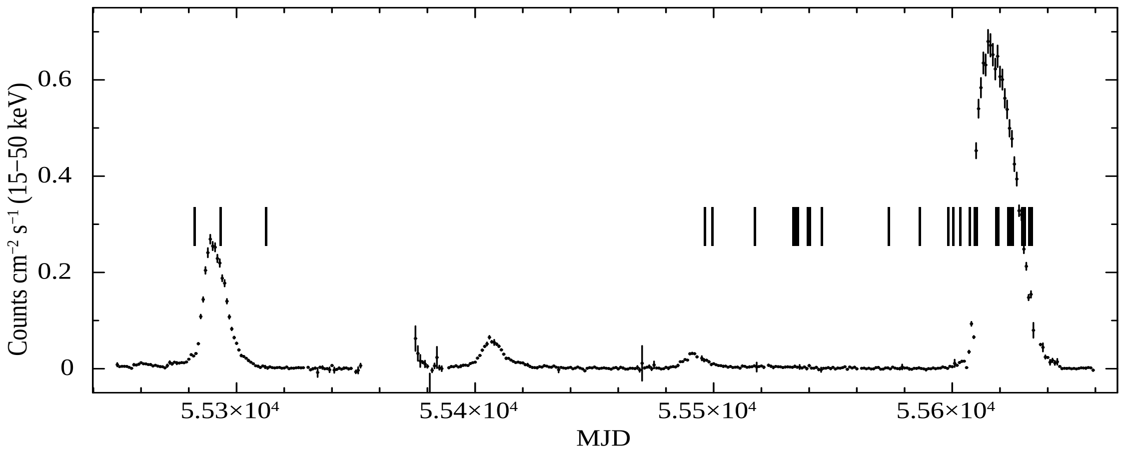

Fig. 1 The *Swift*/BAT light curve of A0535+262 in 15-50 keV energy band, from 2010 February 23 (MJD 55250) to 2011 April 08 (MJD 55659). The regular and periodic X-ray outbursts in the transient Be/X-ray binary pulsar are seen in the light curve. The epochs of our near-infrared observations are marked by vertical lines in the figure.

(Reig 2011). The neutron star in these Be/X-ray binary systems spends most of the time far away from the circumstellar disc surrounding the optical companion. Mass transfer takes place from the Be companion to the neutron star through the circumstellar disc. Strong X-ray outbursts are normally seen when the neutron star (pulsar) passes through the circumstellar disc or during the periastron passage (Okazaki & Negueruela 2001). The X-ray emission of such systems can be transiently enhanced by a factor of $\sim$10 and more. Each of the Be/X-ray binary systems show periodic (Type I) X-ray outbursts that coincide with the periastron passage, giant (Type II) X-ray outbursts which do not show any clear orbital modulation, and/or persistent low luminosity X-ray emission (Negueruela et al. 1998). The Be/X-ray binaries, therefore, attract special interests in several branches of astrophysics (viz. X-ray, optical, infrared bands etc.) to study the effect of the neutron star on the circumstellar disc of the Be star companion.

A0535+262 is a 103 s Be/X-ray binary pulsar discovered by *Ariel V* during a large (Type II) outburst in 1975 (Coe et al. 1975). The binary companion HDE 245770 is an O9.7-B0 IIIe star in a relatively wide eccentric orbit (e = 0.47) with orbital period of $\sim$111 days and at a distance of $\sim$2 kpc (Finger et al. 1996; Steele et al. 1998). The pulsar shows regular outbursts with the orbital periodicity. Occasional giant X-ray outbursts are also observed when the object becomes even brighter than the Crab (Naik et al. (2008) and references therein). The pulsar shows three typical intensity states, such as quiescence with flux level of below 10 mCrab, normal outbursts with flux level in the range 10 mCrab to 1 Crab, and giant outbursts during which the object becomes the brightest X-ray source in the sky with the flux level of several Crab (Kendziorra et al. 1994). Extensive photometric and spectroscopic work in the ultra-violet, optical and infrared bands show the variable nature of the optical companion of the pulsar (Clark et al. 1998a; Haigh, Coe & Fabregat 2004). Infrared spectroscopy of the Be companion HDE 245770 obtained over 1992-1995 showed significant variability implying changes in the circumstellar disc (Clark et al. 1998b). A decrease in the flux of Paschen series lines, strength of Hα line and the optical continuum emission were seen between 1993 December and 1994 September. These changes were attributed to the reduction in the emission measure of the Be disc (Clark et al. 1998b).

A striking episode of circumstellar disc loss and subsequent formation of an new inner disc in the Be binary system A0535+262/HDE 245770 has been reported earlier (Haigh et al. 1999). The Brγ emission line which was earlier seen in emission had gone into absorption, as detected on 1998 November 10 (Figure 4 of Haigh et al. 1999). Along with the change in Brγ line (from emission to absorption), the HeI line at 2.058 μm was also detected in emission with significantly reduced intensity. During this particular disc-loss phase, the Hα emission line was also found to be absent. Following the complete loss of emission, sym-

Table 1 Log of the Mt. Abu near-infrared observations of the Be star in A0535+262/HDE 245770 binary system.

Date of	Spectroscopic Observations			Photometric Observations					
	Integration time (s)			Integration time (s)			Magnitude		
Observation	J-band	H-band	K-band	J-band	H-band	K-band	J-band	H-band	K-band
2010 Mar. 28	200	300	300	230	280	210	7.93±0.04	7.68±0.03	7.26±0.06
2010 Apr. 08	300	300	300	—	—	—	—	—	—
2010 Apr. 27	—	—	—	225	225	53	8.36±0.07	7.93±0.05	7.59±0.37
2010 Oct. 28	—	—	—	250	250	250	7.69±0.02	7.63±0.03	7.42±0.02
2010 Oct. 31	100	120	120	150	150	250	7.62±0.03	7.50±0.02	7.39±0.02
2010 Nov. 18	190	190	190	—	—	—	—	—	—
2010 Dec. 04	120	120	120	—	—	—	—	—	—
2010 Dec. 05	120	120	120	—	—	—	—	—	—
2010 Dec. 06	120	120	120	—	—	—	—	—	—
2010 Dec. 10	—	—	—	150	150	250	7.87±0.03	7.65±0.03	7.44±0.08
2010 Dec. 11	120	120	120	—	—	—	—	—	—
2010 Dec. 16	120	120	120	150	150	250	7.90±0.02	7.70±0.02	7.48±0.03
2011 Jan. 13	120	120	120	150	150	250	7.81±0.01	7.62±0.05	7.49±0.06
2011 Jan. 26	120	120	120	100	100	250	7.98±0.06	7.63±0.02	7.39±0.07
2011 Feb. 07	—	—	—	100	100	250	7.85±0.02	7.64±0.01	7.47±0.02
2011 Feb. 09	180	180	180	100	100	250	7.90±0.02	7.73±0.06	7.46±0.03
2011 Feb. 12	—	—	—	150	150	250	7.89±0.01	7.64±0.03	7.45±0.02
2011 Feb. 16	180	180	150	50	50	25	7.91±0.04	7.66±0.03	7.45±0.04
2011 Feb. 18	180	180	180	150	150	250	7.94±0.03	7.76±0.02	7.47±0.03
2011 Feb. 19	180	240	240	100	100	250	7.98±0.04	7.65±0.04	7.46±0.02
2011 Feb. 27	180	120	120	100	80	200	7.85±0.02	7.71±0.04	7.45±0.04
2011 Feb. 28	180	180	150	100	100	250	7.83±0.02	7.69±0.04	7.51±0.03
2011 Mar. 04	180	180	180	110	165	250	8.02±0.03	7.71±0.02	7.54±0.01
2011 Mar. 05	180	180	180	110	165	250	7.99±0.01	7.73±0.03	7.54±0.01
2011 Mar. 06	180	180	180	110	165	105	7.95±0.01	7.78±0.02	7.48±0.02
2011 Mar. 10	—	180	180	110	165	105	7.98±0.02	7.77±0.03	7.52±0.02
2011 Mar. 11	180	180	180	110	165	105	7.99±0.01	7.76±0.01	7.55±0.05
2011 Mar. 13	—	—	—	50	50	250	7.99±0.02	7.71±0.02	7.54±0.03
2011 Mar. 14	180	180	180	—	—	—	—	—	—

metrical emission wings were formed in Hα and the spectra appeared to remain stable for a few months. The disc-loss state in the Be star HDE 245770, however, has not been seen again. High-dispersion optical spectroscopic observations of the Be star, during a giant X-ray outburst in 2009 November–December, suggested the presence of the active components in the Be circumstellar disc that causes the observed significant variability in the emission line profiles (Moritani et al. 2011). The detection of Hα line in emission, during the giant X-ray outburst, suggest that the disc-loss is not as significant as observed in November 1998.

During the periastron passage of the neutron star in Be binary systems, the circumstellar disc of the Be companion is expected to be most affected. As the contribution of the circumstellar disc towards the total infrared emission from the system is large, the effect of the periastron passage should be pronounced in the infrared rather than optical bands. Hence our motivation for the present IR studies. Our campaign covered the X-ray quiescent and outburst phases of the binary system spanned over four orbital cycles. It may be noted that such a contemporaneous IR coverage of the giant X-ray burst, as presented here, has not been undertaken earlier.

2 OBSERVATIONS AND DATA REDUCTION

Near-infrared spectroscopic and photometric observations of Be star HDE 245770 were carried out by using the 1.2-m telescope of the Mt. Abu Infrared Observatory. As in case of Be/X-ray binaries, regular X-ray outbursts of the Be binary pulsar A0535+262 are detected each time the neutron star undergoes periastron passage using the monitoring detectors onboard various X-ray observatories such as MAXI/GSC, RXTE/ASM, Swift/BAT, INTEGRAL etc. (Nakajima et al. 2010; Mihara et al. 2010; Caballero et al. 2011; Tchernin et al. 2011). Following the detection of X-ray outbursts, the Be star in A0535+262/HDE 245770

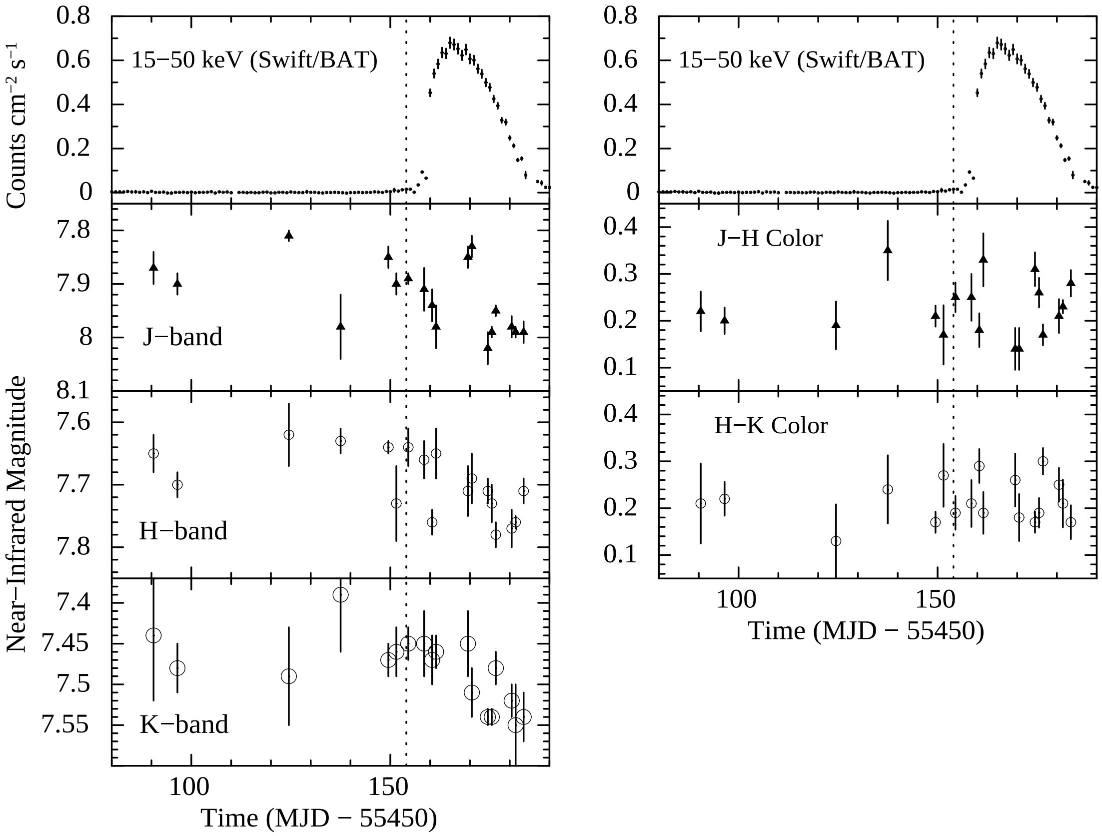

Fig. 2 The Swift/BAT X-ray light curve (in 15-50 keV energy band; top panels) and the near-infrared JHK light curves (left panels) of the Be star in A0535+262/HDE 245770 binary system, covering the recent X-ray outburst in 2011 February-March. The second and third panels in right side show the J-H and H-K colors during the quiescent and outburst phase of the Be/X-ray binary system. The dotted line indicates the onset of the 2011 February–March X-ray outburst.

binary system was observed in radio, optical, infra-red bands at different epochs, the results of which are reported in literature (Giovannelli et al. 2010; Tudose et al. 2010; Mathew et al. 2010; Migliari et al. 2011). We carried out photometric and spectroscopic observations of the Be companion at different orbital phases spanned over three binary periods.

The $Swift$/BAT X-ray light curve of the pulsar in the bianry system covering ∼4 orbital cycles (from 2010 February 23 to 2011 April 08), in 15–50 keV energy range, is shown in Figure 1 with the epochs of our near-infrared observations marked by vertical lines - the log of the observations is given in Table 1. The signal-to-noise ratio (S/N) of the spectral observations were in the range of 20-30, 25-40 and 15-30 for J, H and K-bands, respectively. The Mt. Abu spectra were obtained at a resolution of ∼1000 using a Near-Infrared Imager/Spectrometer with a 256×256 HgCdTe Near-Infrared Camera Multiobject Spectrograph 3 (NICMOS3) array. Photometric observations of the Be star were carried out on several nights (Table 1) in photometric sky conditions using the NICMOS3 array in the imaging mode. Several frames were obtained in five dithered positions, typically offset by ∼30 arcsec from each other, with exposure times ranging from 1–7 s depending on the brightness of the object in JHK bands. The sky frames were generated by median combining the average of each set of dithered frames and subsequently subtracted from the source frames. A nearby field-star SAO 77466, observed at similar airmass as the Be/X-ray binary, was used as the standard star for photometric observations. Aperture photometry was done using the APPHOT task in IRAF.

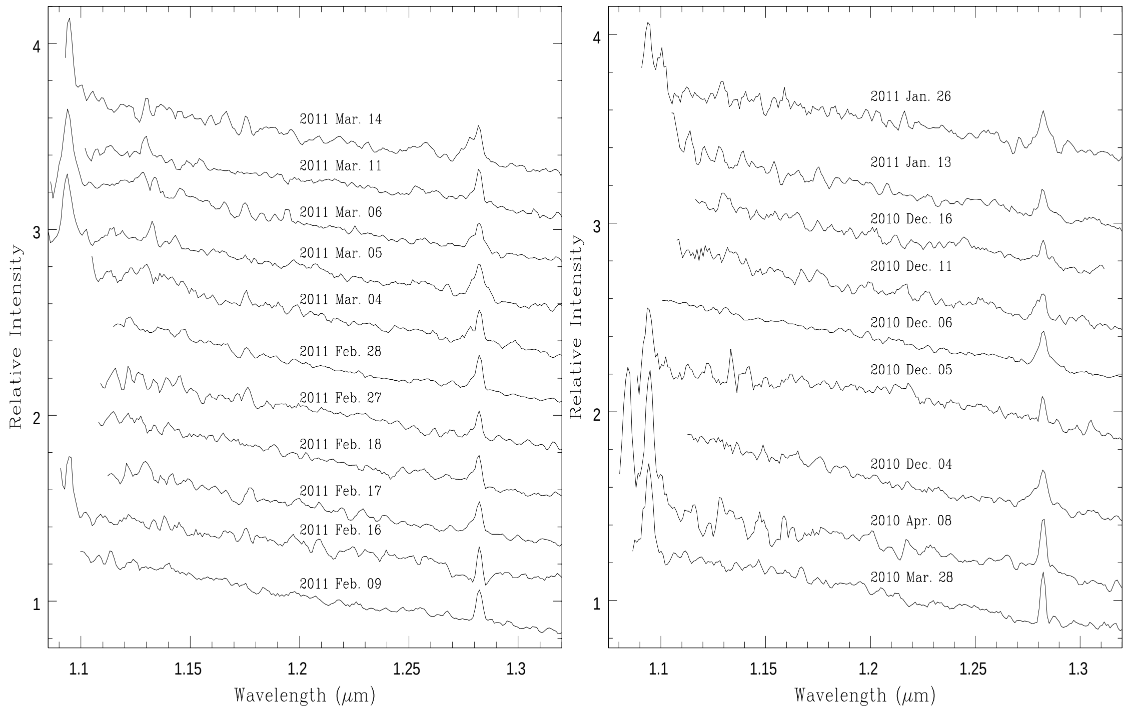

Fig. 3 The J-band spectra of A0535+262/HDE 245770 at different epochs with the continuum being normalized to unity at 1.22 μm.

Spectral calibration was done using the OH sky lines that register with the stellar spectra. The spectra of the nearby field star SAO 76920 were taken in JHK bands at similar airmass as that of A0535+262/HDE 245770 on all the observation nights to ensure that the ratioing process (Be star spectrum divided by the standard star spectrum) removes the telluric lines reliably. The ratioed spectra were then multiplied by a blackbody curve corresponding to the standard star's effective temperature to yield the final spectra. The detailed reduction of the spectral and photometric data, using IRAF tasks, follows a standard procedure that is described in Naik et al. (2009, 2010).

3 RESULTS AND DISCUSSION

3.1 X-ray and infrared JHK light curves of A0535+262/HDE 245770 binary system

The JHK light curves of the optical companion of the transient Be/X-ray binary pulsar A0535+262, obtained from the present photometric observations are presented in second, third and fourth panels in left side of Figure 2. The $Swift$/BAT X-ray light curve of the pulsar (in 15-50 keV energy range) covering the 2011 February–March outburst is also shown in the top panels (left and right sides) of the figure to compare the changes in JHK magnitudes of the companion and corresponding changes in the X-ray intensity during the periastron passage of the neutron star. During X-ray quiescent, the JHK magnitudes of the companion remain almost constant (within errorbars). This represents little changes in the infrared emission during the X-ray quiescent viz. when the neutron star is far away from the Be companion in the binary orbit. However, a gradual and systematic change in the JHK magnitudes of the Be companion is seen since the onset of the X-ray outburst (as marked with dotted lines in Figure 2). Simultaneous increase in the X-ray brightness of the neutron star corroborates the circumstellar disc evacuation/truncation. The $J-H$ and $H-K$ colors, as

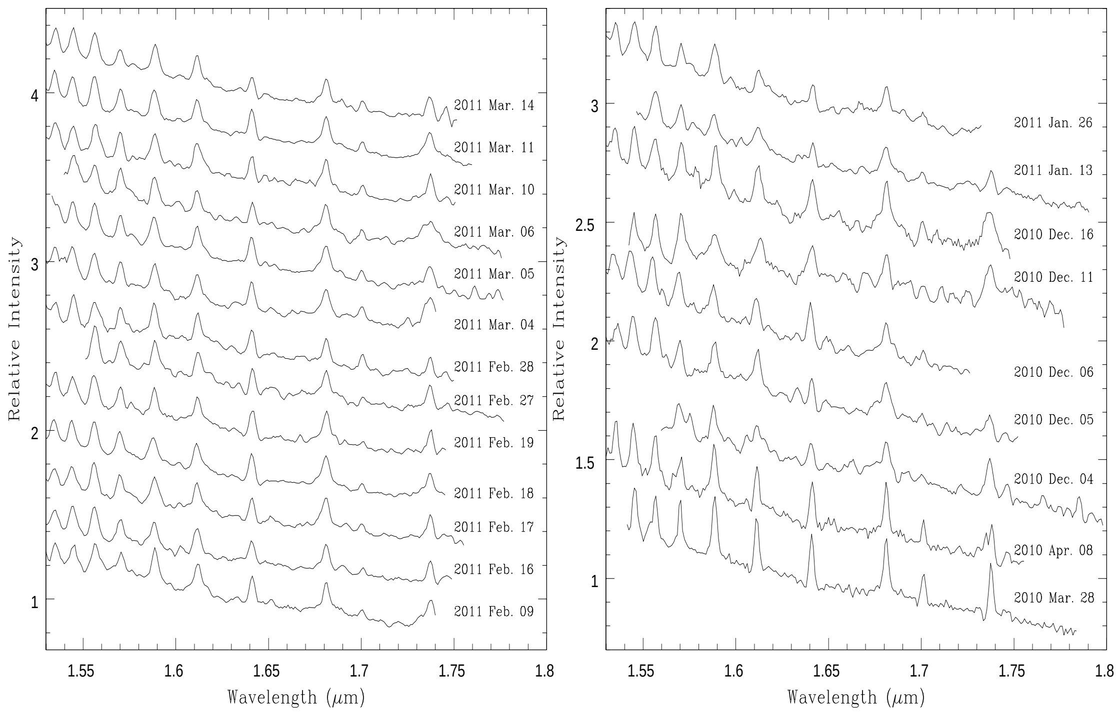

Fig. 4 The H-band spectra of A0535+262/HDE 245770 at different epochs with the continuum being normalized to unity at 1.63 μm.

shown in the second and third panels in right side of Figure 2, do not show any systematic variation during the X-ray outburst. The $J-H$ and $H-K$ values remain constant (within errors) during the quiescent as well as outburst phase of the binary orbital period. This suggests that the reduction in the near-infrared flux during the 2011 February–March X-ray outburst is approximately same in JHK bands.

It is known that the Be circumstellar disc contributes significantly, through free-free and bound-free emission, towards the infrared emission from the Be star system. The observed fading in the JHK magnitudes of the Be companion in A0535+262/HDE 245770 binary system, therefore, can be interpreted as the possible evacuation/truncation of the circumstellar disc around the Be star during the periastron passage of the neutron star. During the X-ray outburst in 2011 February–March, the decrease in the observed JHK photometric magnitudes of the Be star companion is found to be $\sim$0.12. The change in magnitude of $\sim$0.12 in JHK-bands implies a reduction in the source flux by $\sim$12% that arises possibly because of evacuation/truncation of the circumstellar disc during the periastron passage of the neutron star. The amount of matter evacuated from the circumstellar disc of the Be star represents the magnitude of the observed X-ray outburst.

3.2 Emission lines in the JHK spectra

As mentioned earlier, the Be star in the A0535+262/HDE 245770 binary system at JHK magnitudes of $\sim$ 7.5–8.0 (Table 1) is a rather faint and challenging target for the 1.2 m telescope to get good quality near-IR spectrum at the observed resolution of $\sim$1000. Therefore, our primary aim was essentially to record the spectra to look for unusual or drastic changes rather than look for development of new lines or fine changes in the line profiles. For example, we were interested to see whether striking phenomena like a complete disc-loss, that had earlier been reported for the object (Haigh et al. 1999), could be possibly effected by

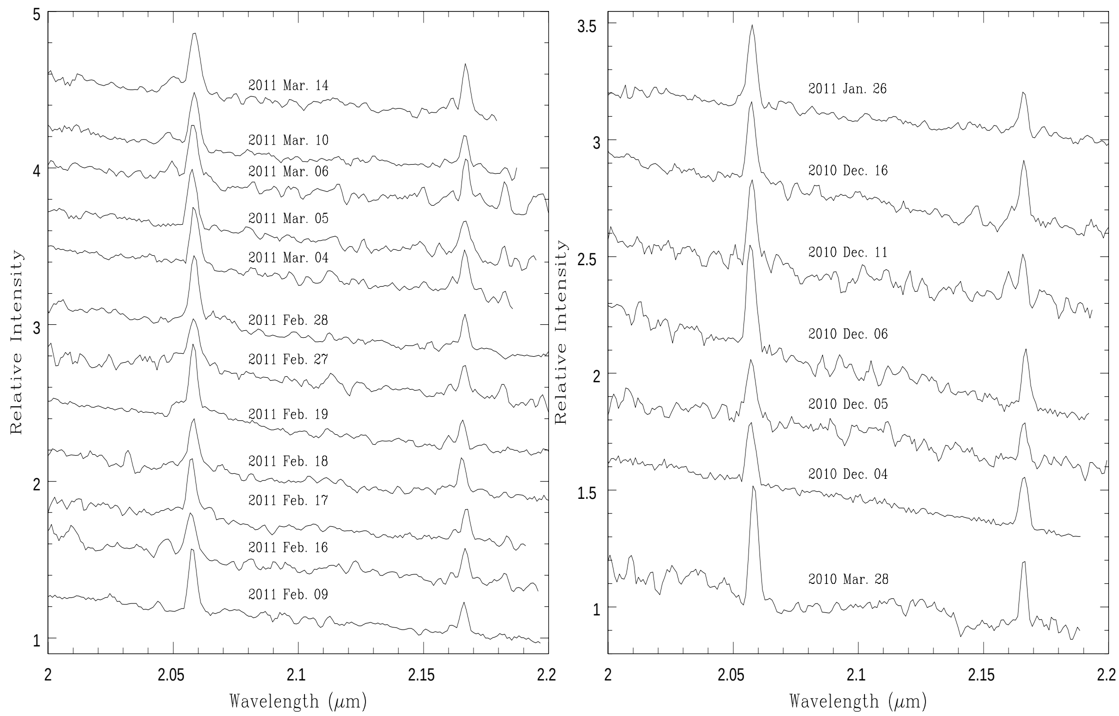

Fig. 5 The K-band spectra of A0535+262/HDE 245770 at different epochs with the continuum being normalized to unity at 2.19 μm.

the neutron star's periastron passage. Such an effect could have been detected in our spectra. Further, we sought to see whether the observed line strengths changed majorly during the X-ray outburst indicating that line-emitting material of the disc had been majorly affected. Such large changes could again be expected to be detectable in our spectra. Our spectra have thus been collected keeping these aims and restrictions in mind and being aware that a deeper study of the near-IR spectra of A0535+262 typically need observations on much larger telescopes as shown by the study of Clark et al. (1998, 1999).

The JHK spectra of the Be star in the A0535+262/HDE 245770 binary system are presented in Figures 3, 4 & 5, respectively. The left panels of Figures 3, 4 & 5 represent the JHK spectra of the Be star since the onset of the 2011 February–March giant X-ray outburst. The spectra in the right panels of the figures, however, are during the rest of our observations that includes the X-ray quiescent phase and a few epochs during minor X-ray outbursts (as shown in Figure 1). The JHK spectra of the Be star, throughout our near-IR observation campaign, display expected emission lines of Paschen and Brackett series lines from hydrogen. The details of the line identification and corresponding equivalent widths are given in Table 2. The HeI line at 2.0581 μm is clearly detected in the K-band spectra during most of the nights of our observation. The HeI line at 1.0830 μm, however, is detected in the J-band spectra during only a couple of nights of observation, as extending the spectrum to cover this line requires a second positioning of the grating in the J-band which was not always possible. The HeI 1.7002 μm line is also prominently seen in the H band. The presence of HeI lines, Brγ and other hydrogen lines in the JHK spectra indicate that the Be star in the A0535+262/HDE 245770 binary system belongs to Group I of the Clark & Steele (2000) classification scheme and its spectral type is earlier than B3 which is consistent with its present classification of O9.7IIIe. A notable feature in the H-band spectra is the structure of the Br11 line at 1.6806 μm which is seen to be distinctly different from other Brackett series lines in terms of both width and shape.

This is most likely caused due to the blending with the FeII 1.679 and FeII 1.687 μm lines which are known to be quite often present in the spectra of Be stars from the H band survey of Steele & Clark (2001).

Apart from these, changes in the shape of several emission line profiles are seen in the JHK spectra of the Be/X-ray binary A0535+262/HDE 245770. At a few epochs during the X-ray outburst, the Paβ and Brγ lines appear to have structures in their profile and may also possibly be blended with other weak emission line. For example, Paβ and Brγ may be contaminated with HeI emission lines at 1.2748 and 2.1614 μm which are sometimes seen in the spectra of other late O/B[e] stars (Hanson, Conti & Rieke 1996; Clark et al. 1999). However, it is difficult to be certain of line profile changes or the presence of such HeI lines in A0535+262 Be/X-ray binary system due to the low resolution and signal-to-noise ratio of the spectral data presented here. Significant variability in the emission line profiles has also been seen in the infrared spectra of Be/X-ray binary A0535+262/HDE 245770 (Clark et al. 1998b). Variability in line profiles was detected from the low and high resolution infrared spectroscopy of the Be binary obtained over 1992–1995 that was interpreted as due to the changes in the circumstellar environment during this time. Strong similarity in the profiles of HeI 1.008, 2.058 μm, Hα and Paschen series lines was also seen in the Echelle spectra of the Be star in this binary system. Optical high-dispersion spectroscopic monitoring observations of the Be binary system showed that the Hα and Hβ line profiles are variable over a period of 500 days (Moritani et al. 2011).

From our study, we find only marginal changes in the strengths of the different lines (Table 2) during the binary orbital phases i.e. during X-ray quiescent and X-ray outburst phases, of the Be/X-ray binary A0535+262. The absence of any major changes in the values of the line equivalent widths at entire orbital phases suggest that the line emitting region in the circumstellar disc, that is closer to the Be star, is not significantly affected by the periastron passage of the neutron star.

We also did a recombination Case B analysis of the HI lines using predicted line strengths given in Storey and Hummer (1995). Visual inspection of the J-band spectra straightaway shows that there is a considerable deviation from Case B conditions. As seen, the strength of Paγ emission line at 1.0938 μm is larger or comparable to that of Paβ at 1.2818 μm - the reverse of this behaviour is expected under case B conditions. We also carried out the recombination case B analysis for the HI Brackett series lines in the H and K band spectra of the Be companion for several epochs of observations at different orbital phases (during X-ray quiescent – before periastron passage of the neutron star and X-ray outburst phase) of the A0535+262/HDE 245770 binary system. Although not shown here graphically there are considerable deviations from Case B conditions. For example, we specifically find that Br γ which is expected to be considerably stronger than the higher Br lines like Br10, 11, 12 etc is consistently observed to be weaker. These results indicate that the Br lines are optically thick causing thereby a deviation from the expected recombination case B strengths. Optical depth effects are not unexpected given that the electron densities in the circumstellar disc of Be stars is generally high in the range of 10^{10} cm^{-3} – 10^{13} cm^{-3} as reported by Steele & Clark (2001).

4 SUMMARY

Near-IR monitoring of the Be/X-ray binary system A0535+262/HDE 245770 during the giant X-ray outburst in 2011 February–March and X-ray quiescent phases, shows a $\sim$12% reduction in the near-IR flux during the periastron passsage of the neutron star. The increase in X-ray brightness during the X-ray outburst could possibly be due to the evacuation of matter from the Be circumstellar disc which was contributing ($\sim$12% during the 2011 February–March X-ray outburst) to the total near-IR emission from the Be binary system. A series of JHK spectra were taken during X-ray quiescent phase and the giant X-ray outburst in 2011 February–March to look for any major changes in the spectra – no such changes were found to take place.

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This was prepared with the RAA LaTeX macro v1.0.

Date	Paβ	Paγ	HeI	Br10	HeI	Br11	Br12	Br13	Br14	Br15	Br16	Br17	Br18	Brγ	HeI
2010 Mar. 28	-8.9	-16.2	—	-7.3	-4.5	-7.1	-6.9	-6.1	-7.2	-4.7	-7.2	-5.6	—	-9.3	-19.4
2010 Apr. 08	-8.9	-21.3	-20.7	-8.8	-2.3	-6.6	-6.1	-4.9	-6.3	-4.8	-5.9	-5.6	-3.8	—	—
2010 Oct. 31	-3.9	—	—	-5.7	-1.8	-6.9	-2.3	-3.7	-3.9	-2.7	-2.8	—	-5.9	—	—
2010 Dec. 04	-12.2	—	—	-8.9	-1.3	-8.3	-4.3	-9.5	-5.2	-4.7	—	—	—	-9.1	-9.1
2010 Dec. 05	-4.4	-17.0	—	-5.6	-1.4	-8.6	-3.8	-5.1	-4.8	-4.3	-5.8	-5.1	-3.1	-5.6	-8.6
2010 Dec. 06	-10.5	—	—	—	-2.2	-8.5	-6.1	-4.8	-4.8	-5.4	-5.2	-5.2	-3.4	-8.2	-13.7
2010 Dec. 11	-9.3	—	—	-9.9	-2.8	-6.8	-5.9	-4.7	-6.7	-8.4	-5.3	-3.9	—	-7.7	-12.8
2010 Dec. 16	-4.2	—	—	-11.6	-2.9	-8.9	-7.4	-6.3	-5.4	-4.1	-4.8	-4.9	-2.4	-9.6	-11.0
2011 Jan. 13	-4.8	—	—	-5.4	-1.3	-5.7	-2.8	-2.8	-3.8	-3.3	-6.4	—	—	—	—
2011 Jan. 26	-9.5	—	—	—	-1.9	-4.3	-2.9	-4.8	-6.3	-3.2	-5.4	-5.8	-2.4	-6.9	-13.3
2011 Feb. 09	-6.4	—	—	—	-1.6	-6.1	-5.3	-7.9	-6.4	-3.5	-6.3	-3.7	-3.5	-6.7	-14.0
2011 Feb. 16	-6.8	—	—	-5.4	-1.8	-7.7	-5.4	-6.6	-6.8	-4.4	-7.5	-6.5	-4.3	-7.0	-12.4
2011 Feb. 17	-5.8	—	—	-7.4	-1.9	-7.8	-7.0	-5.4	-7.1	-5.2	-5.8	-4.5	-3.1	-7.1	-9.9
2011 Feb. 18	-5.9	—	—	-5.9	-1.9	-9.4	-6.7	-5.8	-5.9	-4.5	-5.8	-4.8	-4.1	-7.0	-10.5
2011 Feb. 19	—	—	—	-6.5	-1.2	-7.3	-8.0	-4.4	-4.5	-4.5	-7.7	-4.8	-3.0	-6.2	-11.2
2011 Feb. 27	-4.8	—	—	-5.7	-1.2	-5.2	-6.4	-5.6	-7.3	-5.2	-9.8	—	—	-7.1	-9.1
2011 Feb. 28	-6.5	—	—	-4.5	-2.7	-5.9	-5.9	-5.3	-6.1	-4.1	-4.9	-5.8	-4.9	-6.4	-12.8
2011 Mar. 04	-5.7	—	—	—	-3.2	-8.3	-5.6	-5.0	-5.5	-5.9	-8.8	-4.2	-3.5	-8.9	-12.0
2011 Mar. 05	-7.9	-13.8	—	-8.5	-2.5	-8.8	-5.8	-4.8	-7.6	-4.3	-6.4	-4.3	—	-7.4	-12.5
2011 Mar. 06	-4.1	-21.0	—	-5.0	-3.3	-6.4	-4.7	-5.5	-7.6	-4.3	-4.5	-5.4	—	-9.3	-11.8
2011 Mar. 10	—	—	—	-7.1	-2.9	-6.4	-5.3	-9.6	-7.1	-6.5	-5.5	-5.6	-4.7	-6.5	-13.8
2011 Mar. 11	-6.1	—	—	-6.6	-2.5	-6.8	-5.9	-4.7	-7.2	-4.7	-7.5	-5.5	-4.2	—	—
2011 Mar. 14	-6.1	-13.3	—	-8.7	-3.4	-7.5	-3.5	-5.3	-5.9	-3.6	-5.6	-4.9	-4.0	-11.9	-16.3

Paβ=1.2818 μm, Paγ=1.0934 μm, HeI=1.0830 μm, Br10=1.7362 μm, HeI=1.7002 μm, Br11=1.6806 μm, Br12=1.6407 μm, Br13=1.6109 μm, Br14=1.5881 μm, Br15=1.5701 μm, Br16=1.5545 μm, Br17=1.5439 μm, Br18=1.5342 μm, Brγ=2.1655 μm, HeI=2.0587 μm